GEOCHEMICAL SPACE WEATHERING EFFECTS ON ASTEROIDS: IMPLICATIONS FOR SPACECRAFT INSTRUMENTATION. Jeffrey F. Bell, Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, 2525 Correa Road, Honolulu HI 96822 U.S.A. [bell@pgd.hawaii.edu]

Introduction: For the last 20+ years a debate has raged about the proper association between meteorite classes and their parent asteroids. A large proportion of the asteroid and meteorite communities do not accept straightforward interpretations of asteroid remote sensing data (which samples only the uppermost regolith) as diagnostic of the bedrock composition we see in meteorites. Their principal reason is that many common meteorite types spectrally match rare or non-existent classes of asteroids. Most notorious is the lack of many (any?) asteroids to supply the huge number of ordinary chondrites. Some workers believe that these meteorites come from parent asteroids too small to be measured in current telescopic surveys [1]; others appeal to a variety of "space weathering" processes which cover the observed surface with a regolith spectrally different from the bedrock represented by the meteorites [2]. Virtually all asteroid scientists agree that some such process operates; however, they disagree about the extent to which it conceals the real bedrock composition of asteroids from remote sensing data. Most discussions of this problem have concentrated on *spectroscopic* effects, leaving the (false) impression that chemical compositions are unaffected by "Space Weathering". In this abstract I review evidence that some proposed regolith processes on asteroids could seriously affect interpretations of geochemical data returned by alpha-particle, X-ray, gamma-ray, and other instruments.

Historical background: It was known long before asteroid spectroscopy began that ordinary chondrites (OCs) make up more than 75% of observed meteorite falls. Meteoriticists naturally came to believe that these fall statistics must reflect the proportions of meteorite parent bodies in the asteroid belt. Thus when the first asteroid colors and albedos were obtained in the early 1970s there was a strong expectation that many of the larger asteroids would resemble OCs. When a large class of asteroids proved to have silicate absorption bands similar to those in OCs, many concluded that these objects were the expected ordinary chondrite parent asteroids.

Later, when spectra of ordinary chondrites were measured in the lab it became apparent that they actually had little similarity to S asteroids other than having olivine and pyroxene absorption bands. In particular, the S asteroids have a steep red continuum totally unlike that of the OCs, but resembling that of iron meteorites. This suggested to some that S-class asteroids are differentiated assemblages of metal, orthopyroxene, and olivine, similar to stony-iron meteorites such as pallasites, lodranites, and siderophyres. This material would be the product of melting in the deep interiors of the asteroid parent bodies, subsequently exposed by the collisional disruption.

Thus by the middle 1970s there were two competing paradigms for the composition of S-class asteroids, which both still have vocal defenders today. The key difference in these paradigms is the degree of spectral alteration present in the upper few microns of asteroid regoliths. A variety of specific "space weathering" effects has been proposed to account for the differences between S-class asteroids and ordinary chondrites. Below I consider only those which might have *geochemical* effects:

Impact melting: Chondritic impact melt rocks usually show *depletion in siderophile and chalcophile elements*, due to the segregation and settling of FeNi and FeS during the melting process. In a large-scale melt deposit, these elements could sink below the sensing ranges of any remote instrument, creating the illusion of true igneous differentiation on a chondritic body. Conversely, if the weak upper portion of a melt sheet were eroded away, the lower portion would show *enhancement of siderophiles and chalcophiles* [3,4]

Impact-generated glass: Some workers have suggested the generation of red impact glass or "agglutinates" as an explanation for the S-asteroid problem, since this effect is thought to dominate the reddening process on the Moon [5]. If the uppermost regolith on asteroids is actually glass rich, it could have *spectral, mineralogical,* and *geochemical* differences from the bedrock. *Spectral* studies of glass-rich chondrites suggest that OC impact glass has the reddened continuum of S asteroids [6,7]. Simulations of the glass-forming process with laser beams also produce continuum reddening [8], plus a shift in absorption bands giving a higher apparent ol/pyx ratio. The original *mineralogical* structure of the parent rock is completely destroyed during glass formation. *Geochemical* changes may be produced due to the preferential evaporation of volatile elements from the molten glass. Most lunar agglutinates and glasses are cooled too quickly to show strong volatile depletions, but a class of glass spheres called High-Al Si-Poor (HASP) glass shows almost complete *loss of Na and K*, and strong *depletion of Si*. These spheres are thought to have lost their volatiles during long ballistic flights [7,8]. The lower gravity of asteroids would make HASP-like glasses relatively more common there than on the moon. Thus we may expect the hypothetical glassy upper regoliths of asteroids to give misleading results to visual, IR, alpha, X, and gamma instrumentation on either orbiters or landers.

Differential comminution: Hörz et al. [11] made repeated impacts into a gabbroic target rock at typical main-belt asteroid encounter velocities. It was found that the silicate minerals olivine, pyroxene, and plagioclase break up at slightly different rates during regolith gardening. After many impacts, each mineral takes up a different particle size distribution. Since the spectroscopic methods used to measure the relative abundance of these minerals implicitly assume that the particle sizes of the different minerals are the same [12], this mechanism will produce an apparent shift in mineralogy at the surface. For instance, different particle sizes on the opposite sides of Eros could account for the differences in ol/pyx ratio found there in telescopic observations [13]. The same problem clearly applies to measurements from Galileo or any other future spacecraft.

Differential ejection: The experiments of Hörz et al. [11] did not include measurement of ejecta velocities, so it is not known if ejection velocities of the different minerals varied along with the degree of comminution. Since both processes involve the same physics of fracture, it seems likely that there is some correlation of ejecta mineralogy with ejection velocity, and consequently preferential acceleration of some minerals to escape velocity. On the Moon this effect would be obscured by the high gravity which causes most ejecta to return; but in the micro-gravity environment of an asteroid it could be significant. This effect would produce a real *mineralogical* and *geochemical* difference between bedrock and upper regolith, which would fool X-ray, gamma-ray, and alpha-particle instruments (orbital or landed) as readily as IR instruments. (Hörz et al. found *increasing Al, Ca, and Na* in their finest size fraction, coupled with *decreasing Fe and Mg*).

Enhanced metal fraction: Both differential comminution and differential ejection have special relevance to the Class S asteroid controversy, because the principal mineral at issue here is metallic nickel-iron. (Most advocates of strong asteroidal weathering believe that it is associated with the metal component of chondrites, because the pure-silicate asteroids of classes V, R, A, and E do not exhibit reddening). It is known from the cosmic-ray exposure ages of meteorites that under space conditions metal is much more resistant to impact breakage than any of the silicate minerals in the Hörz et al. experiments. FeNi is also more than twice as dense as any silicate on a grain basis. If iron grains are accelerated to slower velocities than silicate grains during small impacts, the upper regolith will suffer a *real enhancement in Fe, Ni and other siderophile elements*. Curiously, when this process was simulated by magnetic sorting of pulverized OCs, the expected red continuum of iron meteorites was not generated [14]. Neither promoters nor critics of space weathering have ever explained this mysterious result, except to state that "grey" FeNi in chondrites is somehow different than the "red" FeNi in melted meteorites. If so, metal enhancement could not account for the red S-type spectrum. However, any X-ray, gamma-ray, or alpha-particle remote-sensing instrument would probably give anomalously high Fe and Ni abundances. Unfortunatly, this is the basic chemical difference between the competing chondrite-like and lodranite-like interpretations of S-asteroid composition.

Xenolithic components: Mutual collision velocities in the asteroid belt are low enough to allow some material to survive intact. All asteroids are constantly incorporating a small fraction of exotic components into their upper regoliths as part of the gardening process. The most common identifiable macroscopic xenolithic clasts in chondrites are CM-like, and similar material seems to dominate the micrometeorite population. About 1-2% of the average lunar regolith is geochemically CM-like. One might postulate a higher contribution in asteroid regoliths due to the lower impact velocities and lower gravity. This effect might produce an *enhanced volatile element abundance* since CMs are relatively rich in volatiles.

Insights from meteoritic breccias: It might be thought that one could easily determine the importance of the various effects discussed above from studies of meteroritic regolith breccias, which contain solar-wind gases implanted in mineral grains during previous residence at the optical surface of the parent asteroids. In fact, most of the effects discussed above *are* found in regolith breccias, but at very low levels that would not be significant problems in either spectral or geochemical analysis. The problem is that typical breccias have only 5-20% of their matrix grains showing surface exposure effects, the rest being fresh bedrock grains. Therefore, at a minimum, we need to correct the observed effects in breccias by factors of 5-20 to infer their probable level in the actual surface. Indeed, most promoters of strong weathering effects in asteroids completely reject the regolith breccias as valid data sources on upper regolith conditions: "It makes no sense to think that a lithified rock...could be representative of loose, unconsolidated soils at the optical surface of an asteroid" [2]. Logical consistency requires that anyone who advocates the existence of strong spectral weathering effects allow for any of the geochemical weathering effects discussed above.

Conclusions: It is commonly thought that geochemical data from spacecraft will resolve the controversy about space weathering by unambiguously linking S-class asteroids with some meteorite type, either melted or unmelted. It is clear from the literature reviewed above that many proposed weathering processes can affect chemistry in an asteroid's surface layer as well as spectral reflectance. Of the geochemical instruments that could be accomodated on a Discovery-class orbiter or lander, none appears capable of determining the actual bedrock composition. Furthermore, since the various techniques have different effective sampling depths (gamma>X>alpha), they will be sample different proportions of weathered regolith being gardened downward and fresh bedrock being gardened upward. Therefore it will be difficult to merge data from different instruments on the same spacecraft. The only unambiguous solution to this problem is to return a sample of actual non-lithified regolith from an S-class asteroid to Earth, where real weathering processes can be studied and unaltered bedrock clasts identified.

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